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THE ANOMALOUS C IV INTENSITY RATIO IN SYMBIOTIC STARS

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ABSTRACT

The C IV λλ1548.2,1550.8 resonance doublet in a few symbiotic stars exhibit anomalous line intensity ratios in which I(λ1548.2)/I(λ1550.8) $\lesssim$1, or less than the optically-thick limit of unity. Both the R Aquarii-central HII region and RX Puppis exhibit this phenomena. The I(λ1548.2)/I(λ1550.8) ratio in RX Puppis was found to vary inversely with the total C IV line intensity, and with the FES-visual light, as the object declined over a five year period following a brightening in UV and optical emission which peaked in 1982. This doublet intensity behavior could be explained by a wind which has a narrow velocity range of 600 $\lesssim v_{wind} \lesssim$ 1000 km s^{-1}, or by the pumping of the Fe II (mul. 45.01) transition $a^4F_{9/2} - y^4H^o_{11/2}$ by C IV λ1548.2, which effectively scatters C IV photons into the Fe II spectrum in these objects.

Key words: Symbiotic Stars, Stars, Atomic Spectra, Bowen Pumping, Stellar Winds

1. Introduction

Spaceborne ultraviolet spectroscopy in the near and far-UV has afforded investigators an opportunity to explore the complex emission line spectrum of symbiotic stars. These objects are believed to be a class of interacting binary, which contain a red giant or Mira variable, and a hot companion[1]. At optical wavelengths, the presence of an ionizing radiation source in these systems is indicated by the presence of strong nebular emission, which includes [O II], [O III], [N II], [N III] [S II], He I, He II and strong Balmer series emission. In the IUE wavelength sensitivity range, the spectra of symbiotic stars are characterized by an assortment of intercombination lines, which include C III] λλ1907,1909, Si III] λ1892, N III] λλ1749-1750, N IV] λ1487, O III] λλ1660,1666, O IV] λλ1398-1401, as well as the permitted lines of N V λλ1238,1240, Si IV λ1398, C IV λλ548,1550, He II λ1640 and Mg II λλ2795,2802. Often, the Bowen flourescent lines of O III are also quite prominent. A number of symbiotics are sufficiently bright in the UV that high resolution spectra (Δλ ~ 0.1A resolution) are feasible with IUE.

In at least a few of these systems[2,3]; there is a growing body of evidence from the line profile structure of the strong high excitation lines of C IV λλ1548,1550 and He II λ1640 for the presence of high velocity winds of ~900 km s^{-1}; velocities of this magnitude are probably associated with mass expulsion from the hot companion in the system, rather than the extended atmosphere of the late type star. For example, the C IV line profile structure in RX Puppis[4], AG Pegasi[5] and CH Cyg[6] and Z And[7] exhibit broad - complex emission structure, which is probably related to mass motions in these systems, perhaps in the form of streamers or rings, formed as a result of accretion onto the hot companion[4].

In addition to the complex velocity structure suggested in the emission line profiles of RX Puppis, the C IV resonance doublet exhibits additional anomalous properties. Michalitsianos et al. (ref. 8) have noted a curious effect in which the C IV doublet intensities I(λ1548.2)/I(λ1550.8) in RX Puppis and R Aquarii (central HII region) are less than the theoretical optically thick limit of one. Anomalous C IV doublet intensities, where I(λ1548.2)/I(λ1550.8) $\lesssim$1, have also been reported in CH Cyg[6], Z And[7] and AG Peg[5]. In the case of RX Puppis, however, the C IV intensity ratio was I(λ1548.2)/I(λ1550.8) ~ 0.6, during an enhanced phase of UV and optical emission, and became larger, acquiring a value of I(λ1548.2)/I(λ1550.8) ~ 1, as the star declined in UV and visual light over a five year period; i.e. the I(λ1548.2)/I(λ1550.8) was found to vary inversely with the C IV absolute intensity, and with the IUE-FES visual magnitude. This behavior we propose to call the "C IV Doublet Intensity Effect" (ref. 8). The anomalous C IV intensities in RX Puppis have been explained in terms of a high velocity wind which has an expansion velocity in the range 600 $\lesssim v_{wind} \lesssim$ 1000 km s^{-1}. As such, the broad P-Cygni absorption trough of the λ1550.8 red doublet member absorbs emission from the λ1548.2 blue doublet line[8], in a manner similar to that proposed for O and B-type stellar winds[9]. However, a high velocity wind model imposes several important conditions on both the upper and lower limiting wind velocities, as well as the optical depth properties of the expanding gas.

We wish to re-examine this interpretation and consider an alternate possibility, in which **the C IV doublet intensity effect** could be explained if C IV λ1548.2 pumps a high order multiplet (multiplet 45.01) of Fe II in a Bowen type mechanism[10]. This process is suspected to occur in RR Tel and V1016 Cyg, based upon the presence of number of flourescently excited Fe II lines in the LWP $\lambda\lambda$2000-3200 corresponding to the downward cascades of the Fe II $y^4H^o_{11/2}$ transition of multiplet 45.01 [10], even though the C IV doublet ratios in these objects do not appear obviously anomalous.

The merits of both models are discussed in context with our observations of RX Puppis, which have been obtained by monitoring RX Puppis in the *HIRES* and *LORES* mode of *IUE*. Recently, anomalous C IV ratios, I(λ1548.2)/I(λ1550.8) ~ 0.6 have been observed in the central HII region in R Aquarii. On the other hand, the extended 6.″5 nebular jet[11] in this symbiotic system indicates optically-thin emission in C IV, where I(λ1548.2)/I(λ1550.8) ~ 2, appropriate to a photoexcited gas[8]. Thus, the R Aquarii system affords an opportunity to spatially differentiate the C IV line forming regions within its nebulosity in a manner not possible with other more distant, and spatially unresolved symbiotic stars, such as RX Puppis.

2. Discussion

A description of our five year IUE monitoring program of RX Puppis, and the first successful *HIRES exposure of R Aquarii* are described by Michalitsianos et al. (ref. 8). In Figure 1, [top: R Aquarii-HII Region; bottom: RX Puppis] we have overplotted the λ1548.2 and λ1550.8 lines in order to compare their structure in velocity space. The vertical arrows indicate the laboratory rest wavelength. High frequency noise was reduced by a 5-point running average which acts as a digital low-pass filter. The formal fit errors of velocity are ±0.5 km s^{-1}, the instrument velocity resolution at C IV for determining peak emission in well exposed-narrow emission lines is ~ ±2.0 km s^{-1}. Thus, the peak emission for both C IV members is consistent with the radial velocity of R Aquarii of V_R = -23 km s^{-1}, and V_R = +11 km s^{-1} for RX Puppis.

2.1 Line profile Structure

The 5-point smoothing applied to the profiles ensures that high frequency noise has been removed. Therefore, the narrow emission components which survive this smoothing are likely real; this profile structure is also evident in photowrite SWP-HIRES images of both objects. The line profile structure of the C IV doublet in RX Puppis consists of at least three distinct emission components, which have average velocity separations of $\overline{\Delta v}$ ~ 40 km s^{-1}, which over a 5-year period were always seen redward of the rest wavelength. The velocities of these components combine to produce a broadened profile whose base width extends up to + ~125 km s^{-1}. R Aquarii-HII region exhibits similar structure, but the secondary emission component obtained by double-gaussian fitting is blueward of the rest wavelength by a velocity separation $\overline{\Delta v}$ ~ -50 km s^{-1}.

The velocity separation of the individual emission components which form the C IV line profile structure in RX Puppis and R Aquarii are roughly the same, which suggests that the kinematics of the C IV forming regions are probably similar in both objects. If the individual C IV components correspond to discrete parcels of highly ionized gas, which are ejected from the system at roughly regular intervals of time, the predominance of redward displaced emission in the case of RX Puppis, and blueward displaced emission in R Aquarii, might reflect the orientation of ejection if the parcels are emitted successively in a one-sided stream or jet. This is consistent with high resolution radio continuum maps obtained with the Very Large Array (VLA) of RX Puppis and R Aquarii. The 6-cm radio morphology of R Aquarii and its jet clearly suggests that most of the streaming activity is confined to one side of the central object in the form of discrete knots of emission[12]; this is reminiscent of one-sided radio tails in extragalactic jets. Recently obtained high resolution ~0.″1, 1.3 and 2-cm radio continuum observations of RX Puppis also indicate one-sided morphology of a similar nature[13]. The relationship between radio continuum knots and C IV emitting regions could be established only with high resolution sub-arcsecond imaging in *the C IV lines, now only possible with HST.* However, these results provide a preliminary indication establishing a corresondance between radio and UV emission from streaming material in these systems.

2.2 The C IV Doublet Member Intensities

2.2.1 The P-Cygni Profile Interpretation

In Figure 1, the shaded area formed by the superposition of the line profiles shows the velocity range over which the doublet ratio I(λ1548.2)/I(λ1550.8) is less than the optically-thick limit of unity. In the case of RX Puppis, the intensity ratio was I(λ1548.2)/I(λ1550.8) ~ 0.6, when the object was at maximum UV emission around March 1982. Over a five year period, RX Puppis gradually declined in UV line emission. In Figure 2, the I(λ1548.2)/I(λ1550.8) has been plotted against the total C IV doublet intensity for the observing epochs indicated. A linear relationship is evident between the doublet *intensity ratio and UV light. In Figure 3, a* similar relationship was found between I(λ1548.2)/I(λ1550.8) and the FES-visual magnitude for this period as well.

If the "doublet ratio intensity effect" is explained by a wind, a minimum wind speed of 600 to 700 km s^{-1} is required for the doublet wavelength separation of 2.6A, in order for the absorption trough of the λ1550.8 line to absorb emission at λ1548.2. However, continuum adjacent to the C IV doublet has not been detected in long duration SWP-HIRES exposures with sufficient signal to confirm the presence of broad P-Cygni structure; far-UV continuum was not detected in a ~15-hour HIRES-SWP exposure in 1987. Similar duration HIRES-SWP exposures of R Aquarii-HII region also failed to detect adjacent continuum which could support this interpretation. On the other hand, LORES-SWP ($\Delta\lambda$ = 6A resolution) spectra of RX Puppis and R Aquarii clearly indicate the presence of strong UV continuum emission in both objects.

Moreover, if such a high speed wind is present, the curious absence of C IV P-Cygni structure in LORES-SWP spectra in both RX Puppis and R Aquarii places strong upper limits on v_{wind} for both stars of $\sim$1000 km s^{-1}, because of the limiting resolution of LORES IUE spectra. For example, $\sim$1000 km s^{-1} – P-Cygni wind profiles are detectable in LORES-SWP spectra of the planetary nebula IC 418 [14,15]. Accordingly, a narrow range of wind velocities of 600 $\lesssim v_{wind} \lesssim$ 1000 km s^{-1} must exist, which places tight constraints on the wind velocities, such that the V_{wind} is sufficiently large compared with the doublet wavelength separation, but not large enough to be detectable in LORES-SWP spectra.

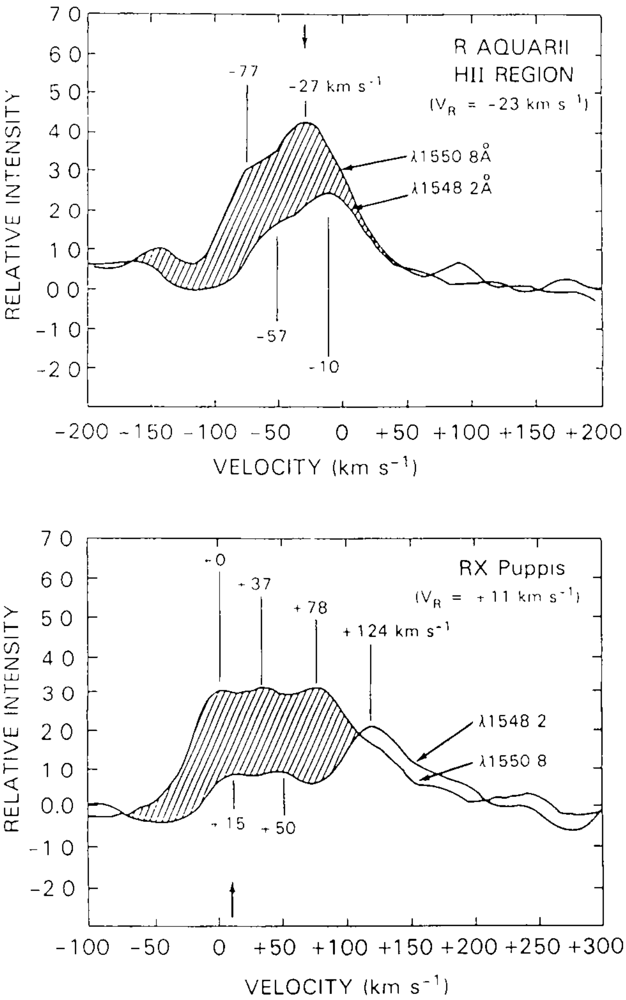

Figure 1: C IV red and blue doublet lines overplotted in velocity space. The vertical arrows indicate the radial velocity of the star. The shaded area indicates the velocity range over which the doublet intensity is less than unity. The velocities shown correspond to the velocity of individual C IV emitting regions that combine to produce the broadened profile.

2.2.2 C IV Bowen Pumping of Fe II

Johansson (ref. 10) identified a number Fe II emission lines of multiplet 45.01 at $\lambda\lambda$2436.20, 2458.78, 2481.00, 2492.28, 2771.15 in HIRES-LWP spectra of the symbiotic V1016 Cyg obtained by Nussbaumer and Schild [16]. These and four additional flourescently formed lines have also been identified in RR Tel [10]; they are formed by the downward cascade of the excited Fe II, $y^4H^o_{11/2}$ level. Emission from C IV λ1548.2 was found by Johansson (ref. 10) to selectively pump the $a^4F_{9/2} - y^4H^o_{11/2}$ transition of Fe II in a Bowen mechanism.

Close examination HIRES-LWP spectra of RX Puppis taken in March, 1982, when the object was at maximum UV emission, and when the C IV I(λ1548.2)/I(λ1550.8) ratio had its maximum deviation below the optically-thick limit of one, indicated only the possible presence of the second strongest line from the group identified by Johansson (ref. 10) in V1016 Cyg and RR Tel, which is Fe II λ2771.2. The strongest member of the series Fe II λ2458.78 was not detected. However, the HIRES-LWP exposure of 180-minutes in March, 1982 was significantly underexposed, making identification difficult for relatively weak features. Accordingly, the only manifestation of the Bowen puming of Fe II by the blue doublet member of C IV could be the anomalous C IV intensity ratio.

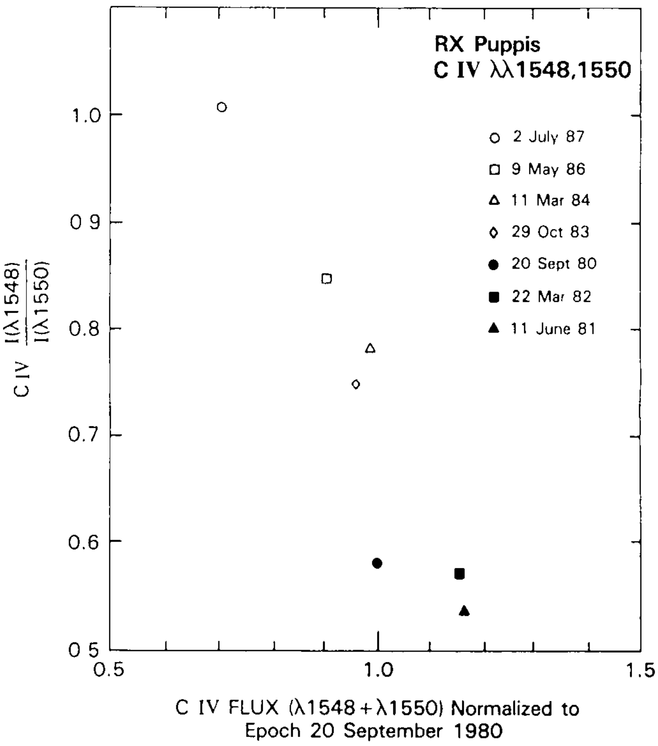

Figure 2: The C IV doublet intensities I(λ1548.2)/I(λ1550.8)-seven observing epochs plotted against the combined C IV emission line intensity.

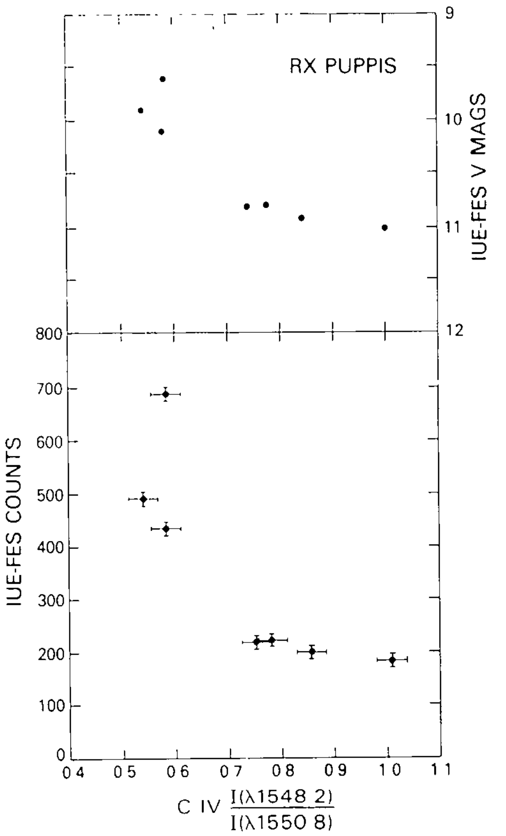

Figure 3: C IV doublet intensity plotted against the FES-magnitudes (top) and the FES counts (bottom).

Similarly, ~15-hour exposures required to detect the strongest emission lines in R Aquarii-HII region in the LWP and SWP HIRES cameras encounter similar difficulties. However, in the case of RX Puppis, IUE has sufficient sensitivity that longer expoures of ~4 hours, for a S/N ~ 10, are possible in the LWP-HIRES camera. If a direct correlation can be established between the C IV I(λ1548.2)/I(λ1550.8) and the strength of the flourescent Fe II lines, the redistribution of C IV energy into the Fe II spectrum of RX Puppis would be important to establish. Because the C IV I(λ1548.2)/I(λ1550.8) ratio is related to the intrinsic UV line brightness, such a correlation could be used to determine concentration of Fe II along the absorbing pathlength during slow outbursts of the system. IUE observations are continuing to investigate this phenomena in greater detail.

3. Conclusions and Summary

The C IV λλ1548.2,1550.8 emission lines in a select number of symbiotic stars exhibit complex profiles, suggestive of complex kinematic motions in the form of streamers, accretion rings and/or a disk [4]. The C IV I(λ1548.2)/I(λ1550.8) intensity ratio also appears anomalous in a number of these systems, where the ratio is less than the theoretical optically-thick limit of unity [8]. In RX Puppis, where this effect has been studied most extensively, the C IV I(λ1548.2)/I(λ1550.8) ratio appears to vary inversely with the total UV line emission.

We have suggested two possible explanations of this behavior which we propose to call the "C IV doublet intensity effect": **i)** the broad P-Cygni absorption trough absorbs emission at λ1548.2, thus reducing the doublet ratio below the optically thick limit of unity during slow outbursts; the wind velocity in this case must be in the range 600 $\lesssim V_{wind} \lesssim$ 1000 km s^{-1}, or, **ii)** that owing to a wavelength coincidence between Fe II and C IV, Fe II (multiplet 42.01) $a^4F_{9/2} - y^4H^o_{11/2}$ transition can be pumped by the blue doublet C IV at λ1548.2 line [10], effectively redistributing C IV λ1548.2 photons into the Fe II spectrum in a Bowen-type mechanism. Present IUE observations can not resolve this issue, and HIRES exposures in the LWP and SWP cameras of IUE, or with the High Resolution Spectrophraph of HST, will be required to probe this effect in greater depth.

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